North Pacific Acoustic Laboratory:
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LONG-TERM GOALS

The ultimate limits of long-range sonar are imposed by ocean variability and the ambient sound field. Uncertainty due to ocean variability limits our ability to make accurate predictions of acoustic propagation. Scattering due to internal waves and other ocean processes limits the temporal and spatial coherence of the received signal. The long-term objectives of the North Pacific Acoustic Laboratory (NPAL) program are to understand the basic physics of low-frequency, broadband propagation in deep water, the effects of environmental variability on signal stability and coherence, and the extent to which acoustic methods, together with other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for acoustic predictions. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques, including matched field processing and other adaptive array processing methods, to capitalize on the three-dimensional character of the sound and noise fields.

OBJECTIVES

A series of long-range acoustic propagation experiments have been conducted in the North Pacific Ocean during the last 15 years using various combinations of low-frequency, wide-bandwidth

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transmitters and horizontal and vertical line array receivers (Worcester and Spindel, 2005). The experiments were designed to investigate the three essential elements of long-range acoustics that form the rationale for NPAL: signal variability resulting from small-scale, relatively high-frequency ocean medium fluctuations, the noise field, and the large-scale background sound speed field. The specific scientific objectives of the most recent NPAL experiment are:

- To explore the range and frequency dependence of the fluctuation statistics and coherence (vertical and temporal) of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments

- To understand the surprisingly large amount of acoustic scattering into the geometric shadow zones beneath caustics previously seen with bottom-mounted SOSUS receivers

- To elucidate the relative roles of internal waves, ocean spice, and internal tides in causing acoustic fluctuations

- To study acoustic scattering and diffraction from bathymetry

- To improve basin-scale ocean now-casts via assimilation of acoustic travel-time and other data into models

- To document the spatial and temporal variability of ambient noise on ocean basin scales

APPROACH

NPAL employs a combination of experiment, data analysis, and simulations to address the issues outlined above. The principal experimental effort during the current phase of NPAL was a deep-water ocean acoustic propagation experiment during 2004–2005 with three closely related components. Our group at Scripps Institution of Oceanography (SIO) had primary responsibility for *SPICEX (Spice Experiment)*, for which two 250-Hz broadband acoustic transceiver moorings and two autonomous vertical line array (VLA) receivers were installed for about one year (Fig. 1). The Applied Physics Laboratory at the University of Washington (APL-UW) had primary responsibility for *LOAPEX (Long-range Ocean Acoustic Propagation Experiment)*, during which a broadband source with a center frequency of about 75 Hz lowered from shipboard during September-October 2004 transmitted to the VLA receivers previously installed by SIO. The source transmitted at ranges varying from 50 km to 3200 km, as well as from an eighth station near the island of Kauai. The Massachusetts Institute of Technology (MIT) and OASIS had primary responsibility for *BASSEX (Basin Acoustic Seamount Scattering Experiment)*, during which a towed horizontal array received the transmissions from the 250-Hz *SPICEX* sources, the 75-Hz *LOAPEX* source, and the ATOC/NPAL source north of Kauai. In addition, the *SPICEX* and *LOAPEX* transmissions, as well as the transmissions from the ATOC/NPAL source north of Kauai, were recorded by APL-UW at U. S. Navy SOSUS receivers. Finally, four Ocean Bottom Seismometers (OBS) were deployed at the VLA site by R. Stephen (WHOI) and J. Colosi (NPS).

To characterize the environment, Underway CTD (UCTD) measurements were made along the path between the VLA receivers and moored sources during the *SPICEX* deployment cruise in June 2004 and during the *LOAPEX* cruise in September-October 2004, providing high-resolution measurements

of the upper ocean. A number of deep CTD casts were also made during these cruises. A Seaglider autonomous vehicle deployed by APL-UW during the *LOAPEX* cruise made measurements along the path beginning in September, before transiting to Kauai for recovery. Finally, a SeaSoar cruise during March 2005 measured upper ocean structure along the acoustic path when the winter mixed layer was fully formed (D. Rudnick, SIO), although the moored sources were no longer transmitting at that time. These data are being used to separate the sound-speed fine structure into two component fields: (i) isopycnal tilt dominated by internal waves and (ii) "spicy" (cold-fresh to hot-salty) millifronts associated with upper ocean stirring, so that the relative roles of internal waves and spice in the scattering of the NPAL transmissions can be evaluated.

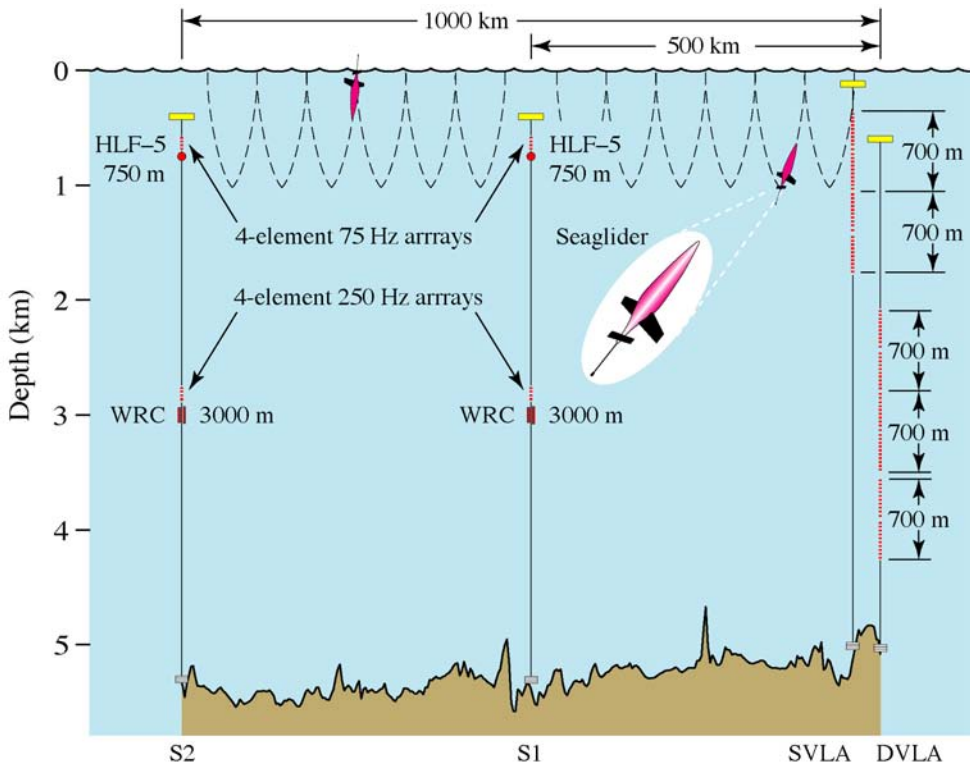

Fig. 1. SPICEX experimental geometry. Two transceiver moorings (S1 and S2) were deployed 500 and 1000 km from two autonomous vertical line array receivers (SVLA and DVLA). One receiving array had a 1400-m aperture spanning the sound-channel axis (Shallow VLA), and the other had a 2100-m aperture spanning a number of lower caustics in the acoustic arrival pattern (Deep VLA). The SVLA and DVLA were separated by about 3 nm. The Seaglider shown is one of several methods used to obtain the necessary environmental data.

WORK COMPLETED

Our tasks during FY2006 included:

Data Processing and Archiving. Our initial task following the 2004–2005 NPAL experiment was the processing and archiving of the VLA data, together with generating the mooring motion and clock

corrections needed in the analysis of the data. We set up a password-protected server to distribute the data, which have now been downloaded by a number of NPAL investigators.

Data Analysis. During FY06 we continued (i) analysis of the 250-Hz transmission data from the *SPICEX* experiment and (ii) further development of the wave-theoretic travel-time sensitivity kernel (TSK) analysis pioneered by Skarsoulis and Cornuelle (2004). The results from these efforts are summarized below. Our intent is to submit manuscripts on both topics by the end of calendar year 2006.

Long-lead-time Experiment Preparations. The 2004–2005 NPAL experiment was the first extended deployment of the Simple Tomographic Acoustic Receiver (STAR) controller and data acquisition systems used in both the HLF-5 and Webb Research Corporation swept-frequency source assemblies. A number of issues, both in hardware and software, came to light as a result. During FY06 the majority of the issues of which we are aware were resolved and first drafts of STAR system documentation prepared.

Looking to the future, one or more long VLA receivers will almost certainly be necessary components of the next deep-water acoustic propagation experiment, which is tentatively planned for FY09 in the Philippine Sea. The VLA receivers originally developed and fabricated for the Acoustic Thermometry of Ocean Climate (ATOC) project have been the workhorses in deep-water, long-range ocean acoustic propagation experiments for over a decade. These systems are now obsolete and becoming difficult to maintain. Furthermore, it is not feasible to deploy arrays greater than 2100 m in length because of the weight of the custom array cables, although full-water-column spanning VLAs are sorely needed to further our understanding of deep-water propagation. We therefore believe that it is time to develop new VLA receiver systems, taking advantage of (i) the STAR controllers and data acquisition systems recently developed at SIO and (ii) the inductive modem technology that is now available. During FY06 we performed preliminary engineering analyses that indicate that it is feasible to develop a modular near-water-column spanning VLA using distributed, self-recording hydrophones with timing and scheduling provided by one or more central STAR controllers via communication links using inductive modems. The enabling technology for this approach is the availability of small flash memory modules that can store several gigabytes of data at each hydrophone, so that the communication link connecting the hydrophone packages to the central controllers can be relatively low bandwidth. The array cable needed for use with inductive modems is simply standard 3 x 19 jacketed oceanographic wire rope, rather than a custom electromechanical cable. The vision is that self-recording hydrophones can be clamped to standard mooring wire wherever desired at the time of deployment, making the VLA readily configurable for different experiments.

RESULTS

SPICEX 250-Hz Transmissions. The 250-Hz acoustic transceiver moorings each had (i) a 250-Hz HLF-5 source located at a nominal depth of 750 m, approximately on the sound channel axis, which transmitted broadband, phase-coded m-sequences, and (ii) a Webb Research Corporation (WRC) swept frequency source located at a nominal depth of 3000 m, approximately at the surface conjugate depth, which transmitted linear FM sweeps from 225–325 Hz. The Shallow VLA (SVLA) receiver had a 40-element, 1400-m long array centered approximately on the sound channel axis (350–1750 m nominal). The Deep VLA (DVLA) receiver had a 60-element, 2100-m long array (2150-4270 m nominal) to span the lower caustics in the acoustic arrival pattern. It contained upper, middle, and lower AVATOC data acquisition systems, to record data from the upper, middle, and lower 700-m

sections of the array, respectively. The middle AVATOC had a slow leak through an underwater connector, however, and no useful acoustic data were recorded.

High signal-to-noise ratios were obtained at the SVLA and DVLA receivers from the moored 250-Hz sources 500 and 1000 km distant. Figure 2 shows the measured timefronts at the DVLA from the HLF-5 source 500 km distant, together with predicted timefronts using a range-dependent sound-speed field constructed by combining Underway CTD (UCTD) data from the upper ocean with deep CTD data at the source and receiver mooring locations, both obtained during the SPICEX deployment cruise. Even at this relatively short range the measured timefronts at the DVLA extend well into the geometric shadow zones below the lower caustics, with energy visible up to 500–600 m below the predicted caustic depths. (The earliest branches of the timefront at this range extend below the deepest depth sampled by the DVLA, however.) Similar results are found for receptions from the HLF-5 source 1000 km distant from the SVLA and DVLA, except that at 1000 km range the early, surface-reflected branches of the timefront do not extend as far into the geometric shadow zone as the later refracted arrivals.

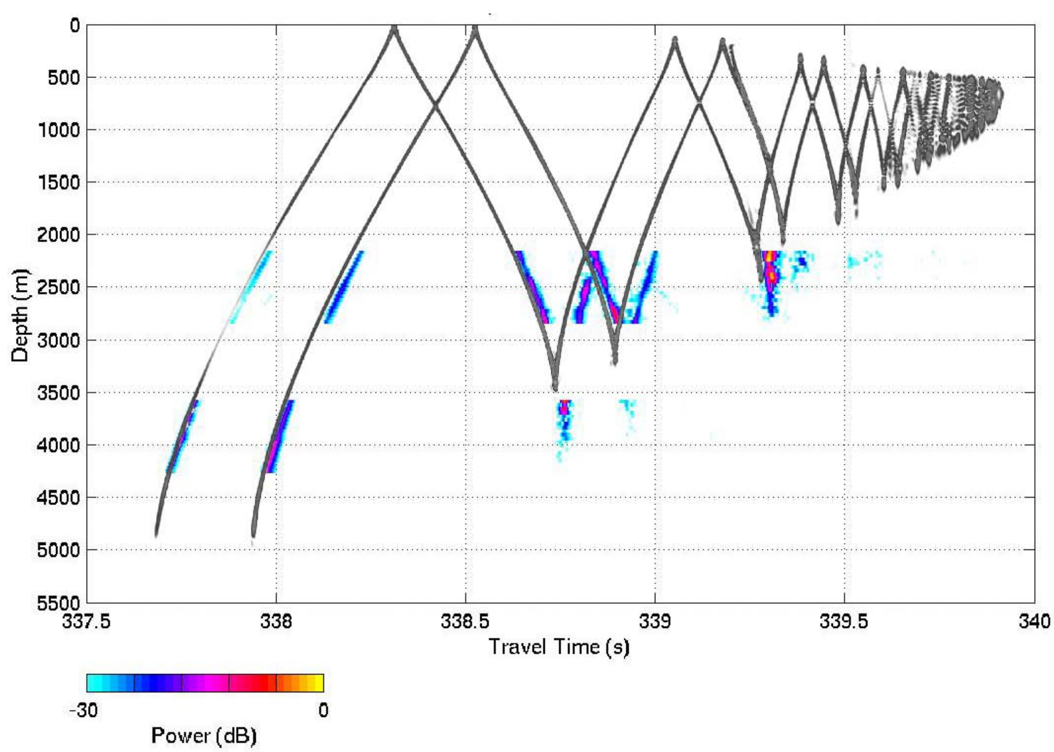

Fig. 2. (Color) Measured timefronts at the DVLA receiver from the HLF-5 source 500 km distant at 20:35:42, 11 June 2004 (UTC), shortly after deployment. (Gray-scale) Predicted timefronts using a range-dependent sound-speed field constructed by combining Underway CTD (UCTD) data from the upper ocean with deep CTD data at the source and receiver mooring locations.

Simulations including internal waves with roughly one-half the energy level in the Garrett-Munk spectrum are able to account for the observed vertical scattering in the reception finale, but higher internal-wave energy levels or other mechanisms seem necessary to account for the early shadow zone arrivals. We suspect that the key to understanding the shadow-zone arrivals lies in the upper ocean, where the Garrett-Munk internal-wave model is not appropriate. One possibility is that internal-wave

induced fluctuations in the base of the mixed layer, where the vertical sound-speed gradients are strong, may be a particularly important source of scattering that affects the deep turning points. Rudnick and Munk (2006) have made estimates of scattering from the base of the mixed layer under the assumption that acoustic rays are reflected by the high sound-speed gradient there. The problem is then not dissimilar to surface scattering, except that the random fluctuations in the depth of the base of the mixed layer due to internal waves are much greater than surface wave amplitudes. They find that acoustic energy is scattered into the geometric shadow zones below caustics, with the extent of the scattering proportional to the number of reflections from the base of the mixed layer (i.e., range). The result is that the scattering is roughly comparable to that observed in the data, but some caution is appropriate as the UCTD data do not show a well-developed mixed layer at the time of the SPICEX deployment.

Finally, receptions from the abyssal sources show scattering occurring predominantly along the acoustic time fronts, as previously suggested by simulations, rather than across them (not shown).

Full-wave Acoustic Sensitivity Kernels. Ray theory has long been the model used when trying to reconcile ocean acoustic measurements with environmental parameters. For ocean acoustic tomography, measured travel time changes are ascribed to sound-speed changes along the unperturbed ray path. Since sound is governed by the wave equation, the travel time can be affected by environmental changes that are not on the geometric ray path, however. The goal of this work is to understand the extent to which this happens and to determine the validity of the ray approximation.

The full-wave acoustic sensitivity kernel is a map in physical space of the change in the acoustic measurement for a given change in environmental parameters (the Frechet derivative). This could be calculated by brute force, but a mathematical formulation of the problem relying on the Born approximation and the principle of reciprocity allows a much simpler (although still challenging) computational problem (Skarsoulis and Cornuelle, 2004). We have extended this work to include the effects of range dependence and can now calculate the kernel using the RAM parabolic equation propagation code (Collins, 1993) for much more realistic ocean environments.

Figure 3, for example, shows the sensitivity as a function of range and depth of the travel time of a single resolved arrival to changes in sound speed, for a 250-Hz source (Q=3) at 750 m depth and a receiver at 2500 m depth and 100 km range. Alternating blue and red bands show zones of negative and positive sensitivity centered more-or-less on the geometric ray path, with negative sensitivity along the ray path as expected. The width of first Fresnel zone is demarcated by the first zero crossing from blue to red. There is clearly sensitivity that extends beyond the first Fresnel zone. There are also a number of higher wave number features that have no ray equivalent. The key to understanding this picture is to transform it to wave number space, as shown in Fig. 4. Sound travels in a nearly horizontal line between the source and receiver. (The physical scales are greatly distorted in Fig. 3.) In wave number space this gives a nearly vertical line. As the sound is refracted between up-going and down-going rays in physical space, the vertical line in wave number space rotates back-and-forth slightly, giving the hourglass shape in Fig. 4. The vertical extent of Fig. 4 is set by the wavelength of the sound transmitted. Thus we can think of these pictures as the physical and wave number space representations of the forward acoustic scattering function. The heavy black lines in Fig. 4 show the maximum extent of internal wave perturbation scales as given by the Garrett-Munk spectrum. This shows that the sound has sensitivity to perturbations with far higher wave numbers, perhaps extending to the density-compensated “spicy” finestructure (Dzieciuch *et al.*, 2004).

Mean and rms travel-time sensitivity kernels calculated when internal wave scattering is added to the environment shows that the geometric ray model is a reasonable one in many situations, depending on the scale sizes of the perturbations. Nearly all our results to date are for 2-D geometries, however, and the results may differ when fully 3-D geometries are considered.

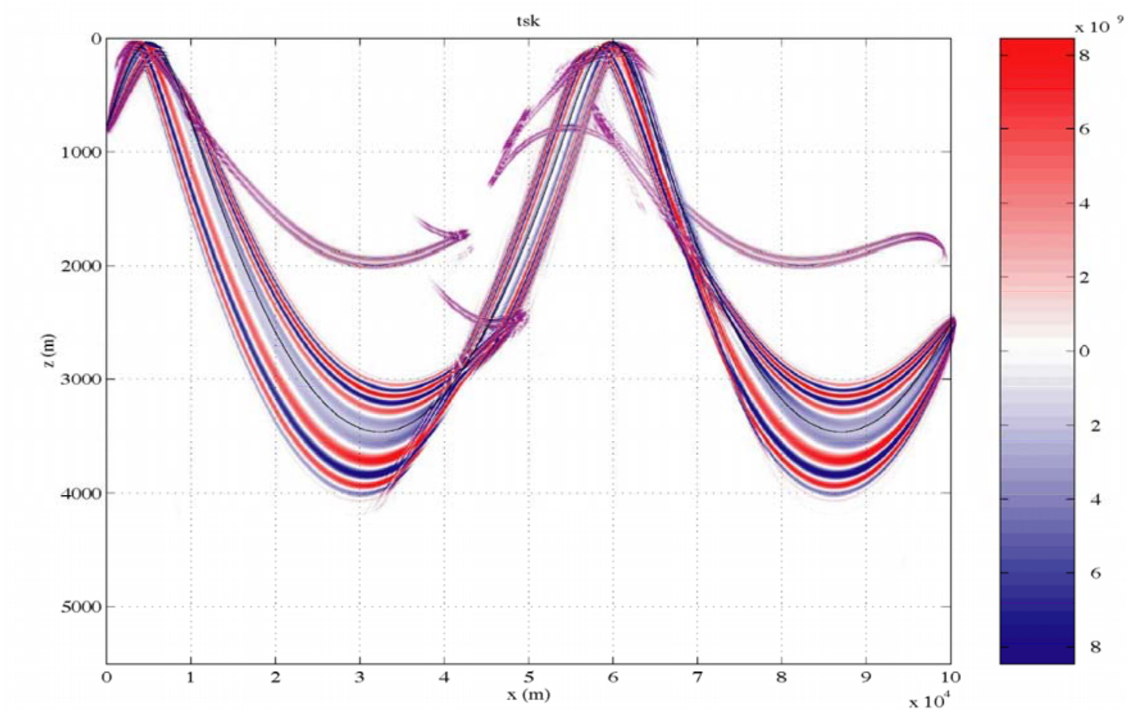

Fig. 3. The sensitivity as a function of range and depth of the travel time of a single resolved arrival to changes in sound speed. A 250-Hz source (Q=3) is at 750 m depth on the left, and the receiver is at 2500 m depth and 100 km range on the right. The geometrical ray path (black line) contains two complete ray loops. Alternating blue and red bands show zones of negative and positive sensitivity centered more-or-less on the geometric ray path, with negative sensitivity along the ray path as expected.

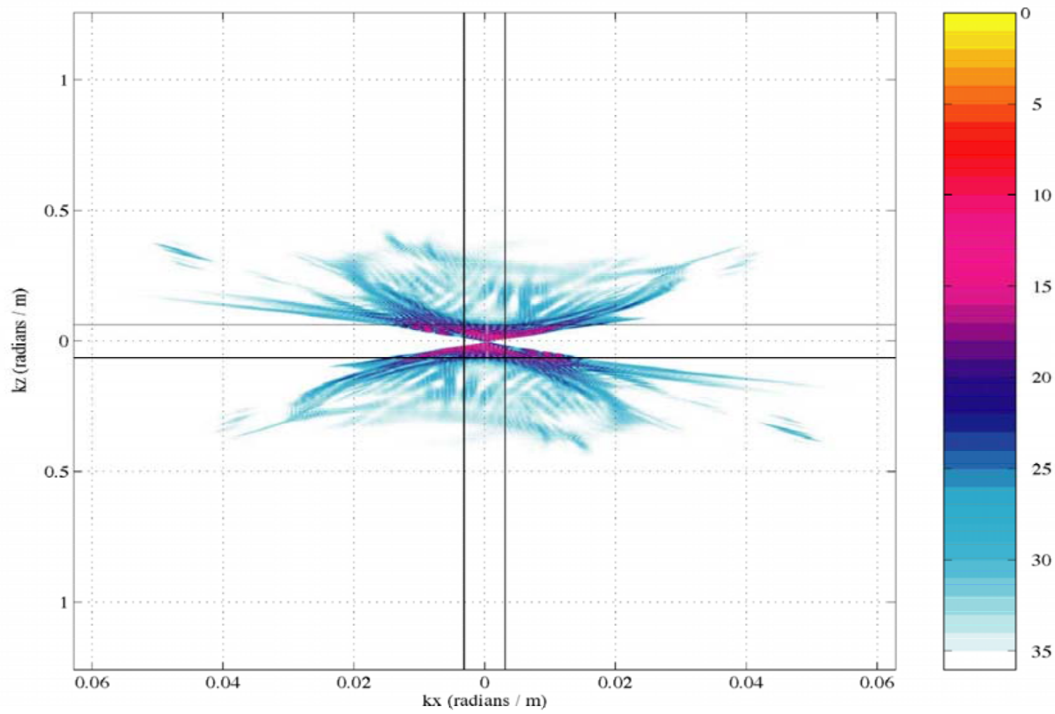

Fig. 4. The two-dimensional Fourier transform of the travel-time sensitivity kernel in Fig. 3, showing its structure as a function of horizontal and vertical wave number. The heavy black lines delineate the maximum extent of internal wave perturbations as given by the Garrett-Munk spectrum.

IMPACT/APPLICATIONS

This research has the potential to affect the design of deep-water acoustic systems, whether for sonar, acoustic communications, acoustic navigation, or acoustic remote sensing of the ocean interior. The data indicate that existing systems do not begin to exploit the ultimate limits to acoustic coherence at long range in the ocean.

TRANSITIONS

Simple Tomographic Acoustic Receiver (STAR). SIO and Webb Research Corporation (WRC) previously collaborated to integrate the STAR four-channel receiver and source controller developed by SIO into the swept frequency acoustic sources developed by WRC. The STAR and the integrated STAR/WRC swept frequency source system are much more cost-effective and significantly easier to use than the previous generations of acoustic receivers and transceivers employed in long-range propagation and ocean acoustic tomography experiments. Two STAR data acquisition systems are currently being used by the Naval Postgraduate School in the Windy Island Soliton Experiment (WISE). Other potential users have expressed interest in the STAR receivers and/or the STAR/WRC swept frequency sources, including the Nansen Environmental and Remote Sensing Center (Bergen, Norway).

RELATED PROJECTS

A large number of investigators and their students are currently involved in ONR-supported research related to the NPAL project. The Principal Investigators include R. Andrew (APL-UW), A. Baggeroer (MIT), F. J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), B. Dushaw (APL-UW), S. Flatté (UCSC), N. Grigorieva (St. Petersburg State Marine Technical Univ.), K. Heaney (OASIS), F. Henyey (APL-UW), B. Howe (APL-UW), J. Mercer (APL-UW), A. Morozov (WRC and WHOI), V. Ostachev (NOAA/ETL), D. Rudnick (SIO), E. Skarsoulis (IACM/FORTH), R. Spindel (APL-UW), R. Stephen (WHOI), M. Vera (U. Southern Mississippi), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), and M. Wolfson (APL-UW).

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HONORS/AWARDS/PRIZES

Peter F. Worcester, Scripps Institution of Oceanography, University of California, San Diego, The Walter Munk Award (2006), Awarded in Recognition of Distinguished Research in Oceanography Related to Sound and the Sea by The Oceanography Society, the Office of Naval Research, and the Office of the Oceanographer of the Navy.